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Discharge Equation for Proposed Self-cleaning Device

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Abstract. To minimize the sedimentation problems upstream of weirs and to increase the capacity and accuracy of these devices, a combination of a V-notch weir and a rectangular sluice gate was proposed and studied experimentally. Different models with different geometric combinations were tested. These geometries include, gate opening, gate length and V-notch angle. Experiments were conducted for free gate flow (unsubmerged) conditions on horizontal and sloping channels. Results showed that flow passes through the device is affected by the device geometry and the flow parameters. Semi-empirical discharge equation was developed. The equation represents the collected experimental data well with an absolute error less than 4%.

Notations

B	width of the flume
b	gate breadth
C	a defined coefficient
C_{VG}	a defined coefficient for the combined discharge
C_{VGD}	the combined discharge coefficient derived from the dimensional analysis
g	gravitational acceleration
H	upstream flow depth
h	flow depth above the weir crest
Q_{CA}	actual combined discharge
Q_{cr}	theoretical combined discharge
Q_G	theoretical sluice gate discharge

R_e	Reynolds number
Z_G	sluice gate opening
Z_V	height of the weir crest from the bed of the flume
ΔZ	obstruction length
W_c	weber number
μ	viscosity
p	density
σ	surface tension
θ	apex angle of theV-notch weir.

Introduction

Weirs are commonly used to control flow in open channels and as flow measuring devices. The requirements for accurate measurements and their advantages and disadvantages can be found in the literature, see e.g. Ackers *et al* [1], Bos [2], BSI [3], USBR [4-5].Sharp crested weirs are commonly used. They may be classified according to their shape and whether they are contracted or suppressed. The rectangular contracted weir and the V-notch weir are examples of sharp crested weirs which are used frequently for discharge measurements in irrigation channels. Discharge equations for different types of weirs can be found in many sources; Ackers *et al* [1], Bos [2], French [6], Herschy [7]. Swamee [8] gave a generalized equation for rectangular weirs. The v-notch weir has the advantage of measuring low flow ranges accurately and has a wider practical range of flows than any other shape. Although weirs are convenient to use, when proper conditions for measurements are maintained, they may not be suitable when the flow carries debris that could settle in the approach channel. Deposition of the silt and debris upstream of weirs will reduce the accuracy of such devices and hence periodic cleaning is needed. To overcome such disadvantages and enhance the accuracy of weirs, a device which will minimize deposition of debris upstream of weirs is proposed. In addition, this device will function similar to weirs or gates as a control and discharge measurement device. Also minimum maintenance is needed as most of the floating materials and sediments will pass through the device. For existing weirs, gate may be provided for temporary flushing out deposited materials. This device may have wide applications in irrigation channels in arid and semi-arid regions where such problems are encountered.

Little information is available in the literature regarding such types of devices where the flow passes simultaneously over and below the structure, see e.g. Chow [9] and Naudascher [10]. Negm *et al* [11] discussed the characteristics of the simultaneous flow over contracted rectangular sharp-crested weirs and below triangular gates. In 1995, Negm[12] investigated the characteristics of the combined flow over weirs and below triangular gates. In 1995, Negm [12] investigated the characteristics of the combined flow over weirs and below gates of rectangular shape with unequal contractions. Recently, Alhamid *et al* [13] developed a linear regression equation to predict the combined flow over the rectangular weir and below a triangular gate. They stated that the maximum absolute error is about 5% at 95% confidence limit. In this paper, the hydraulic characteristics of the proposed device were studied experimentally for different geometrical combinations under varied flow conditions with free flow downstream and device.

Theoretical Analysis

The combined flow over a sharp crested V-notch weir and beneath a contracted sluice gate is sketched in Fig.1. For upstream flow depth below notch crest, only sluice gate flow exists.

For this condition and from energy principle, the theoretical flow passes through the gate can be written as:

$$Q_G = Z_G\, b\sqrt{2gH} \tag{1}$$

in which Q_G= the theoretical discharge of the sluice gate, Z_G= opening of the sluice gate, b= breadth of the sluice gate, H = the upstream flow depth and g = the gravitational acceleration. As upstream flow depth exceeds the weir crest, combined flow conditions occurs (i.e. over the weir and under the gate) with a total theoretical discharge of:

$$Q_{CT} = Z_G b\sqrt{2gH} + \frac{8}{15}\tan\left(\frac{\theta}{2}\right)\sqrt{2gh}^{5/2} \tag{2}$$

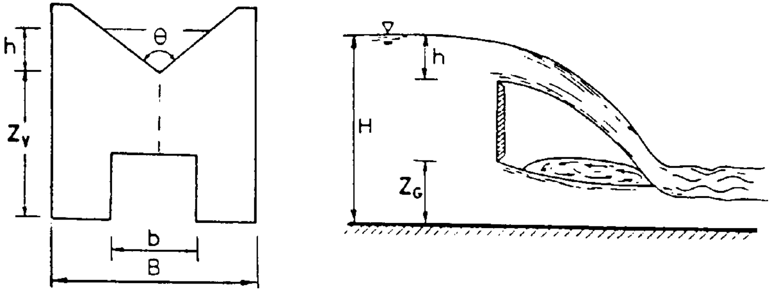

Fig. 1. Definition sketch for the simultaneous flow over weirs and below gates.

in which Q_{cT} = the theoretical combined discharge, θ = the angle of the V-notch and h = is the flow depth above the weir crest. The second term of Eq. (2) is the well known V-notch discharge equation. Introducing a coefficient of discharge, C_d, to account for the difcrences between the simplified theory (from which Eq.(2) was derived) and reality, the actual discharge, Q_{CA},may be written as:

$$Q_{CA} = C_d\,(Z_G b\sqrt{2gH} + \frac{8}{15}\tan\left(\frac{\theta}{2}\right)\sqrt{2gh}^{5/2} \tag{3}$$

Rearranging and expressing in dimensionless form, Eq.(3) becomes:

$$C_{VG} = \frac{Q_{CA}}{Z_G b\sqrt{2gH}} = C_d\left(1+\frac{8}{15}\tan\left(\frac{\theta}{2}\right)\frac{h^{5/2}}{Z_G bH^{1/2}}\right) \tag{4}$$

in which C_{VG} is a defined duscgarge coefficient. It is expected that C_d is dependent on the geometry of the device as well as the flow conditions (i.e. Z_G, Z_v, b, H, B, and θ) and hence it follows that C_{VG} is also a function of the geometry of the boundary and the flow conditions. A better understanding may be obtained by utilizing dimensional analysis. The actual combined discharge can be written in functional form as:

$$Q_{CA} = \Phi_1\,(g,\rho,\mu,\sigma,Z_G,Z_V,b,B,\theta,H,h,\Delta Z,S_o \tag{5}$$

in which ρ = the water density, μ = the water viscosity, σ = the water surface tension, and Z_V = the height of the weir crest. Using the principle of the dimensional analysis, Eq. (6) is obtained:

$$C_{VGD}\frac{Q_{CA}}{\sqrt{gH^{5/2}}} = \Phi_2\left(R_e,W_e,\frac{Z_G}{H},\frac{Z_V}{H},\frac{b}{B},\theta,\frac{h}{b},\frac{\Delta Z}{H},S_o\right) \tag{6}$$

in which R_e = Reynolds number = g $H^{3/2}/(\mu/\rho)$, W_e = Weber number = H g/ (σ/ρ), and C_{VCD} = discharge coefficient from dimensional analysis. For water at a specific temperature, ρ, μ, and σ are constant,hence, R_c and W_c can be represented by one dimensional variable H, Ackers [1]. Thus Eq. (6) is reduced to;
Alternatively (7) may be re-written in the following form:

$$C_{VGD} = \frac{Q_{CA}}{\sqrt{gH^{5/2}}} = \Phi_3\left(H,\frac{Z_G}{H},\frac{Z_V}{H},\frac{b}{B},\theta,\frac{h}{b},\frac{\Delta Z}{H},S_o\right) \tag{7}$$

$$C_{VGD} = \frac{Q_{CA}}{\sqrt{gH^{5/2}}} = \Phi_3\left(\frac{Z_G}{Z_v},\frac{Z_V-Z_G}{H},\frac{b}{B},\theta,\frac{H-Z_V}{B},S_o\right) \tag{8}$$

Comparing Eq. (8) withEq.(4) it can be seen that:

$$C_{VGD} = \sqrt{2}C_{VG}\left(\frac{Z_G b}{H_2}\right) \tag{9}$$

Apparently, Eq.(8) may also be written as:

$$C_{VG} = \frac{Q_{CA}}{Z_G b\sqrt{2gH}} = \Phi_4\left(\frac{Z_G}{Z_V}, \frac{Z_V - Z_G}{H}, \frac{b}{B}, \theta, \frac{H - Z_V}{B}, S_o\right) \tag{10}$$

Apparatus and Tested Models

Experiments were conducted on a glass sided rectangular flume. The flume is 9 mm long, 30.5 cm wide, and 30.5 cm deep. The water depths were measured by point gauges having accuracy up to ±0.1 mm. The discharge through the flume was measured by a pre-calibrated V-notch installed in a measuring tank. The measuring tank is located below the outlet of the flume at its downstream end and connected directly to an underground sump. Water is delivered to the flume by a centrifungal pump. The flume is equipped with a tail gate to control the tailwater depth. Ten models with different geometries combination were tested. Each model behaved as a V-notch weir at its top and as a contracted sluice gate at its bottom. Details of the tested models are given in Table 1. The models were fabricated of perspex sheets, 12 mm thick, with all interior edges bevelled at 45° with sharp edges about 1 mm thick. The sides of the models were sealed with rubber sheets to ensure no leakage from the sides. Models were fixed at the middle of the flume to ensure uniform flow upstream of the model and to minimize the effect of the downstream tailgate. The models were tested on horizontal as well as 0.77% and 1.61%bed slopes for discharges ranging between 5 l/sec and 25 l/sec.

Table 1. Details of the tested models

Model No.	θ^o	b (cm)	Z_G (cm)	Z_G/Z_V
1	90	10.0	10.0	0.50
2	90	15.0	10.0	0.50
3	90	15.0	5.0	0.25
4	90	20.0	5.5	0.275
5	90	5.0	10.0	0.50
6	90	20.0	8.0	0.40
7	60	15.0	5.0	0.25
8	60	20.0	8.0	0.40
9	45	20.0	8.0	0.40
10	30	20.0	8.0	0.40

Flow Characteristics

The dimensionless discharges (Q_{CA} /g $H^{5/2}$) for all models are plotted against the obstruction ratio (i.e. ratio of obstructing length to the flow depth = (Z_v - Z_G)/H) in Fig. 2. It can be seen that the data are grouped in a complex way indicating the effect of the different parameters of the proposed device (i.e. b/B,Z_G/Z_V and) on Q_{CA}/g $H^{5/2}$. The effect of these parameters on the flow are discussed later. Generally speaking, the dimensionaless discharge is increasing with the increased obstructing ratio. Figure 3 is plotted out of Fig. 2 to show the effect of bed slope on the discharge through the device. This is found to be of minor importance compared to the other parameters which may be due to the limited range of slopes of the test flume.

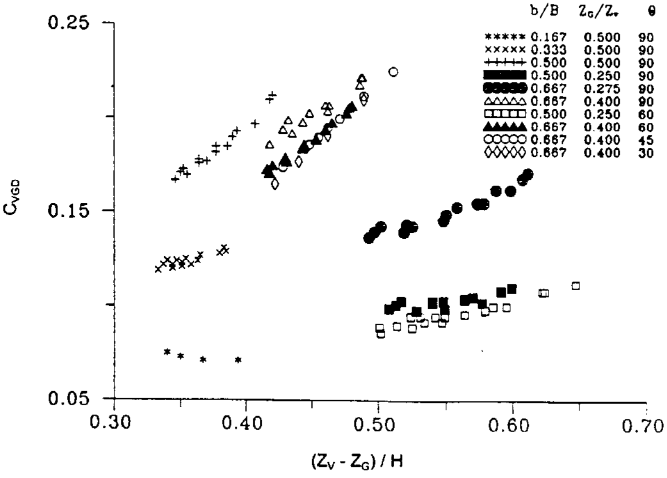

Fig. 2. Variation of C_{VGD} with (Z_V-Z_G)/H for different b/B, Z_G/Z_V and θ.

Effect of Z_G/Z_V ratio

For the same b/B and θ, the effect of Z_G/Z_V ratio is shown in Fig. 4. It can be seen that the higher the Z_G/Z_V ratio (or in other words the lesser the obstructing depth) the higher the dimensionless discharge value. Also, as the Z_G/Z_V ratio decreases, the variation of the dimensionless discharge with the obstruction ratio will be flatter. Since Z_V is kept constant in this experimental set-up, the ratio of Z_G/Z_V increases as the height of the

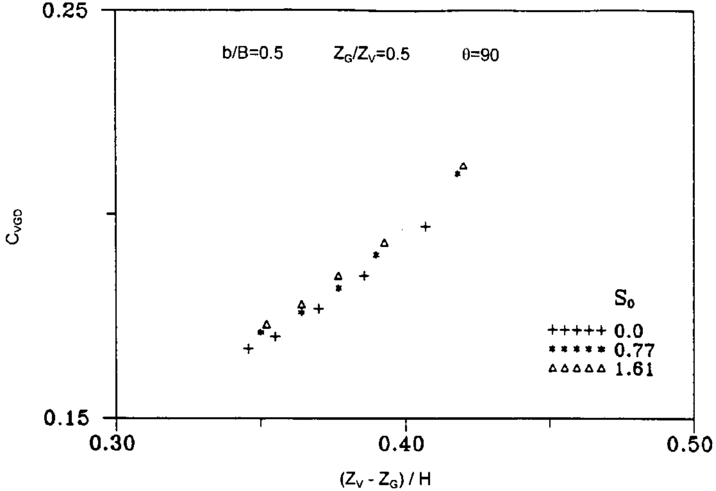

Fig. 3. Effect of bed slope on the variation of C_{VGD} with $(Z_V-Z_G)/H$ for typical model with b/B=0.05, Z_G/Z_V=0.05 and θ=90°.

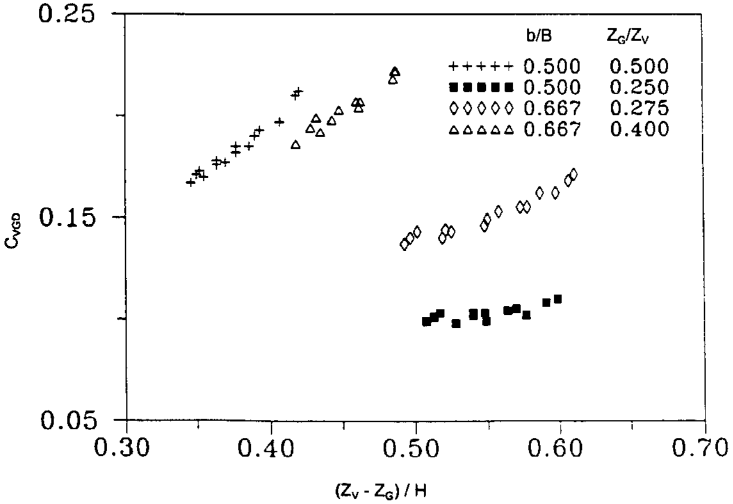

Fig. 4. Effect of Z_G/Z_V on the variation of C_{VGD} with $(Z_V - Z_G)/H$ for b/B=0.05 and 0.667.

lower opening is increasing. Therefore, the dimensionless discharge has to increase. The larger the gate opening the larger the flow.

Contraction effect

The ratio of the gate breadth to the flume width denotes the contraction ratio, b/B. Minimum contraction effect occurs at maximum contraction ratio (i.e. when b/B approaches unity) and maximum contraction effect occurs at minimum contraction ratio (i.e. when b/B approaches zero). The contraction effect on the dimensionless discharge values are shown graphically in Fig. 5, in which the variation of $Q_{CA}/ g \ H^{5/2}$ versus $(Z_V - Z_G)/H$ is plotted for different b/B ratios at $Z_G/Z_V = 0.5$ and $\theta = 90$. The higher the contraction ratio (the wider the gate compared to the flume width), the higher the discharge values.

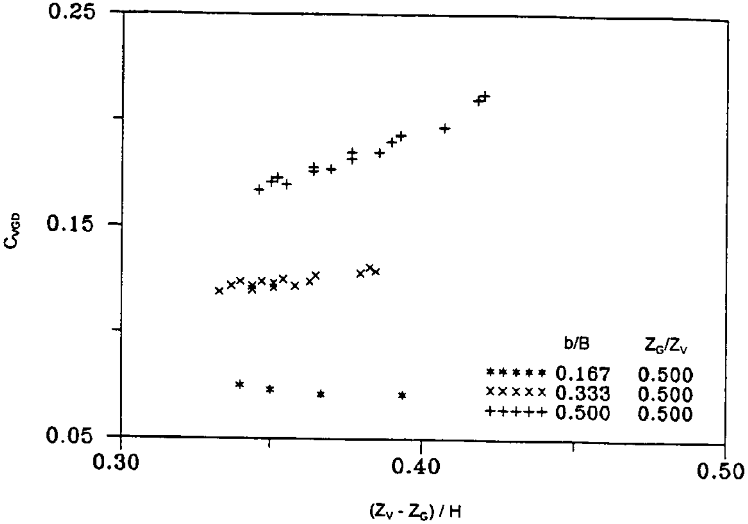

Fig. 5. Effect of b/B on the variation of C_{VGD} with $(Z_V/Z_G)/H$ for $Z_G/Z_V = 0.5$.

Effect of the V-notch angle, θ

For b/B equals to 0.667 and Z_G/Z_V equals to 0.4, the dimensionless discharge values versus the obstruction ratios are shown in Fig. 6 for different v-notch angles. It is apparent that the wider the angle, the higher the discharge value for the same obstruction ratio. As $(Z_V - Z_G)/H$ is increased, the effect of θ is decreased and the data tend to make a unique line. This sounds reasonable because as H decreases, the notch area will be almost similar for different angles and hence the effect of notch angle becomes minimum. In other words, for smaller H values most of the flow passes through the gate and the impact of the v-notch is minimal. As H increases the relative portion of the flow through the V-notch increases having a greater influence on the total combined flow.

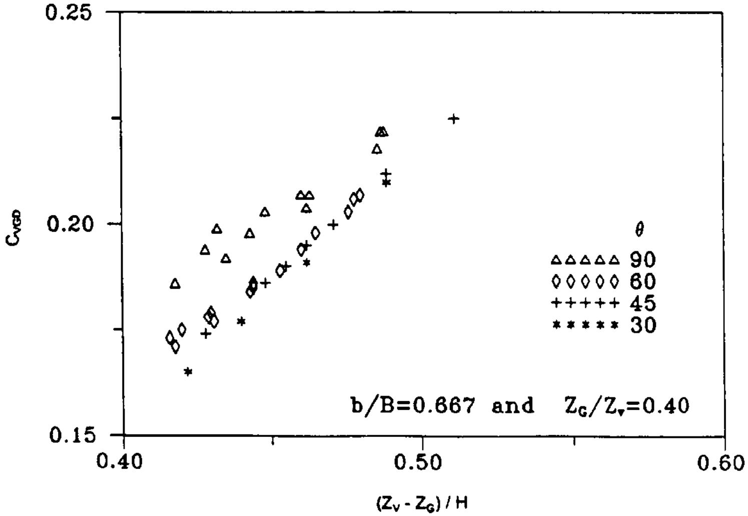

Fig. 6. Effect of q on the variation of C_{VGD} with $(Z_V-Z_G)/H$ for $b/B = 0.667$ and $Z_G/Z_V = 0.4$.

Discharge Equation

The parameters of the proposed device played an important role in the discharge values and have a complex behavior. Using non-linear statistical analysis and based on Eqs. (10) may forms of equations for the discharge coefficient, C_{VG}, were tried by introducing different combinations of the parameters and evaluating the effect of these combinations on the estimation of the combined discharge coefficient. Out of these trials an equation was obtained for discharge coefficient C_{VG} in the form:

$$C_{VG} = \left(0.8405 + \frac{2.41125\left(\tan\left(\frac{\theta}{2}\right)\right)^{0.49786}\left(\frac{H-Z_V}{B}\right)^{1.56249}}{\left(\frac{Z_V-Z_G}{H}\right)^{-1.75956}\left(\frac{Z_G}{Z_V}\right)^{0.32516}\left(\frac{b}{B}\right)^{0.52167}} \right)^4 \tag{11}$$

This equation estimates C_{VG} with maximum error less than 5% in which more than 90% of the data points have an error less than 3% Figure 7 shows the computed and the actual values of the discharge coefficient C_{VG} in which a good fit is observed. Equation (9) is valid within the following limitations:

- $0.30 < (Z_V - Z_G)/H < 0.70$;
- $0.17 < b/B < 0.5$;
- $30 < \theta < 90$;
- $0.25 < Z_G/Z_V < 0.5$ and
- $Z_V < H$.

Combining equations (4) and (11), the combined discharge can be computed from the following equation:

$$Q_{CA} = C_{VG}\, Z_G b \sqrt{2gH} \tag{12}$$

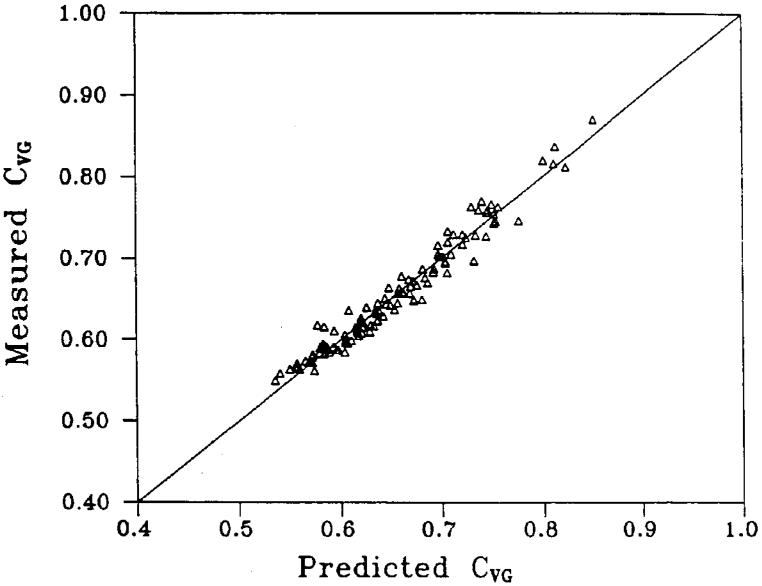

Figure 7. Comparison between measured and computed C_{VG} values.

Conclusions

A proposed discharge measurement device was investigated experimentally. This device composed of a sharp crested V-notch weir and a rectangular contracted sluice gate. This device overcame some of the deficiencies of weirs and gates in sediment laden flows. It can be used in irrigation networks in arid and semi-arid regions to regulate and measure the flow. The present study proved that both the flow and the geometric parameters played an important role on the amount of flow that passes through the device. Semi-empirical equations,(11) and (12), were suggested for computing the combined discharge through the proposed device. The effects of the different parameters on the combined discharge are discussed and presented in graphical form. These parameters are included in the developed equation which shows a good fit with the experimental data.

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معادلة للتصرف لجهاز مقترح ذاتي التنظيف

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ملخص البحث. تم اقتراح جهاز ذاتي التنظيف مكوّن من هدّار مثلث الشكل وبوابة مستطيلة الشكل حيث يفيد هذا الجهاز في التقليل من تراكم الرواسب أمام الهدّار والحد من المواد الطافية أمام البوابة وكذلك يفيد في زيادة كمية التصرف لكل من الهدّار والبوابة.

ولقد أجريت دراسة معملية على الجهاز المقترح باستخدام العديد من النماذج ذات الأبعاد المختلفة للبوابة وزوايا متعددة للهدّار. وأجريت التجارب في قناة مستطيلة المقطع وبميول مختلفة تحت ظروف التدفق الحُر للبوابة.

وقد أظهرت نتائج هذه الدراسة أن كمية التصرف المار خلال الجهاز تعتمد مباشرة على كميات لابعدية تمثل كلا من الخصائص الهندسية للجهاز وخصائص التدفق. وتم اقتراح معادلة لحساب التصرف المزدوج باستخدام معامل تصرف واحد فقط. حيث استخدم التحليل غير الخطي لإيجاد معادلة دقيقة لحساب معدل التدفق بدلالة الكميات اللابعدية المختلفة المؤثرة على كمية التصرف. وقد أظهرت هذه المعادلة المقترحة دقة عالية مقارنة بالنتائج المعملية حيث إن نسبة الخطأ لم تزد على ٤٪.